

COMMENT ON “DARK MATTER SEARCHES GOING BANANAS: THE CONTRIBUTION OF POTASSIUM (AND CHLORINE) TO THE 3.5 KEV LINE”

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ABSTRACT

The recent paper by Jeltema & Profumo (2014) claims that contributions from K XVIII and Cl XVII lines can explain the unidentified emission line found by Bulbul et al. (2014) and also by Boyarsky et al. (2014a,b). We show that their analysis relies upon incorrect atomic data and inconsistent spectroscopic modeling. We address these points and summarize in the appendix the correct values for the relevant atomic data from AtomDB.

1. INTRODUCTION

In a recent preprint “Dark matter searches going bananas: the contribution of Potassium (and Chlorine) to the 3.5 keV line,” Jeltema & Profumo (2014, hereafter JP) claim that the unidentified $E \approx 3.55\text{--}3.57$ keV emission line that we detected in the stacked galaxy cluster spectra (Bulbul et al. 2014, hereafter B14) and Boyarsky et al. (2014a) detected in Perseus and M31 (as well as their more recent detection of the same line in the Galactic Center, (Boyarsky et al. 2014b)) can be accounted for by an additional Cl XVII Ly β line and by broadening the model uncertainty for the flux of the K XVIII He-like triplet. These transitions occur at $E \approx 3.51$ keV, close to our unidentified line. In B14, we considered the K line among other possibilities and concluded that it cannot explain the new line. Here we respond to JP’s concerns, focusing on our galaxy cluster analysis.

Specifically, JP raise three key points about the analysis in B14:

1. A possible Cl XVII Ly β line at $E = 3.51$ keV was not included in our model;
2. The plasma temperatures derived from the ratios of fluxes of S XVI, Ca XIX and Ca XX lines in the cluster spectra are inconsistent, thus a much larger range of temperatures must be allowed in modeling;
3. When using a wider range of possible temperatures, and scaling from the fluxes for the S XVI, Ca XIX, Ca XX lines reported by B14 for the Perseus cluster, the total flux in the K XVIII and Cl XVII lines can match that of the unidentified line.

They conclude that, accounting for these points, no additional line is required by the B14 data. We address these items below.

1.1. Atomic Data

In a study of this nature, using accurate atomic data is vital. JP state that they have used AtomDB (Smith et al. 2001) to calculate their line fluxes. Though they do not cite the version, from the fact that they used the recently added lines of Chlorine, it must be the latest version 2.0.2 (Foster et al. 2012). However, we have been unable to recreate the line ratios in Table 3 of JP using

AtomDB v2.0.2. In theory, these should be the fluxes from their Table 2, multiplied by the ratio of predicted K XVIII emissivities to that of the line in question.

We can, however, recreate their Table 3 if we use the approximate values available in the “strong lines” option at <http://www.atomdb.org/WebGUIDE/webguide.php>. As described on that page, this option uses an approximation

$$\epsilon(T) = \epsilon(T_{peak})N(T)/N(T_{peak}) \quad (1)$$

where ϵ is the emissivity, T is the requested temperature, T_{peak} is the temperature for which the transition’s emissivity is its maximum, and N is the abundance of the ion. This approximation is intended for quick identification of possible strong lines, as it disregards the change in line emissivity with temperature, instead accounting only for the relative change in ion abundance.¹

Using these approximate data, we were able to recreate the values in JP’s Table 3 exactly from the data in Table 2, to identify exactly which lines JP included in their flux ratio calculations, and to explain the line ratios discussed in their §3.1. The error due to the use of this approximation can be very large for temperatures away from the line peak emissivity temperature, as illustrated in Fig. 1 for our four relevant lines.

1.2. Line Ratios as Temperature Diagnostics

Incorrect atomic data easily lead to incorrect conclusions about the gas temperature structure based on the observed line ratios. In particular, JP find that the observed ratios of the S XVI, Ca XIX, Ca XX lines (the lines used in B14 to estimate the K XVIII flux) indicate very different plasma temperatures. (Of course, in a single-component plasma in ionization equilibrium, all line ratios must correspond to the same temperature.) Therefore, they conclude that the plasma has to have a very complex temperature structure, and so B14 were not justified to restrict the temperature range for our estimates of the K XVIII flux. We will address the K line in the next section, and here we check if the relevant line ratios are indeed in disagreement.

¹ A note that accompanies the results of every line search on that web page further states: “The emissivities listed here are intended only as a guide, and should not be used for analysis ... For correct emissivities, please use the full AtomDB database.”

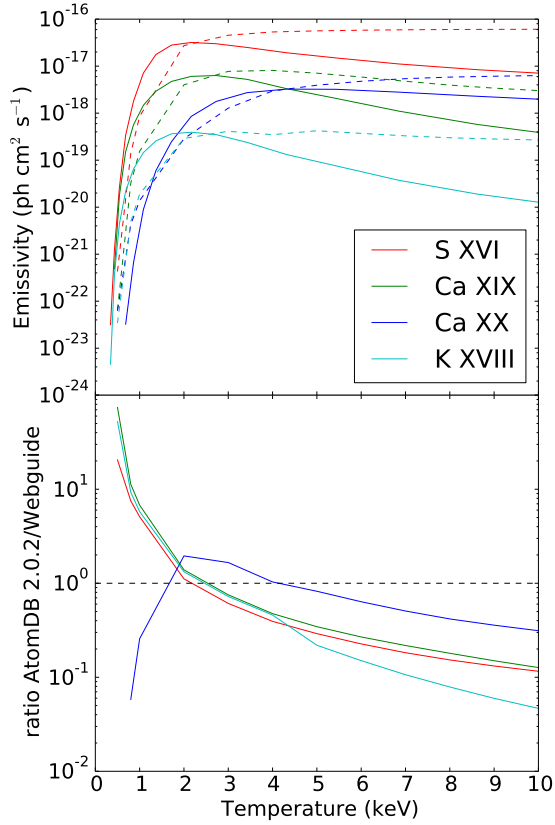


FIG. 1.— Upper panel: emissivities for the relevant lines as a function of temperature. Solid curves show the correct data from AtomDB 2.0.2, and dashed lines show those from the WebGUIDE “strong lines” approximation. Lower panel: ratios of the correct emissivities to the “strong line” emissivities for the same lines.

Figure 2 shows the line ratios of the above 3 lines as a function of temperature, assuming solar photospheric abundances (Anders & Grevesse 1989), using the correct AtomDB data (solid curves, our calculation) and the WebGUIDE approximation used by JP (dashed curves). Colored horizontal bands show the ranges of the observed ratios for the various cluster subsamples given in B14. Vertical gray bands show JP’s temperature ranges implied by these observed ratios (based on the intersection of the dashed theoretical curves with the observed bands), which are indeed very different. However, the correct line ratios aren’t quite as inconsistent with each other; in fact, with a reasonable (factor ~ 2) reduction of the relative S/Ca abundance (dotted curves in the two upper panels), all three agree with the observed range of ratios around $T \sim 3 - 4$ keV.

However, to exclude the effects of relative elemental abundances on line diagnostics of the plasma temperature, it is best to use the line ratios for different ions of the *same* element. Since we (and JP) are most concerned with the presence of cool plasma components, a particularly useful diagnostic is the S XV $n = 2 \rightarrow 1$ triplet at $E = 2.45$ keV. It should be very strong in sub-3 keV plasma — as shown in the lower panel of Fig. 3, it exceeds the already strong S XVI line at $E = 2.62$ keV once the temperature drops below 2 keV. The upper panel of Fig. 3 shows the line ratios for S XVI/S XV and Ca XX/Ca XIX (the latter is the same ratio shown in

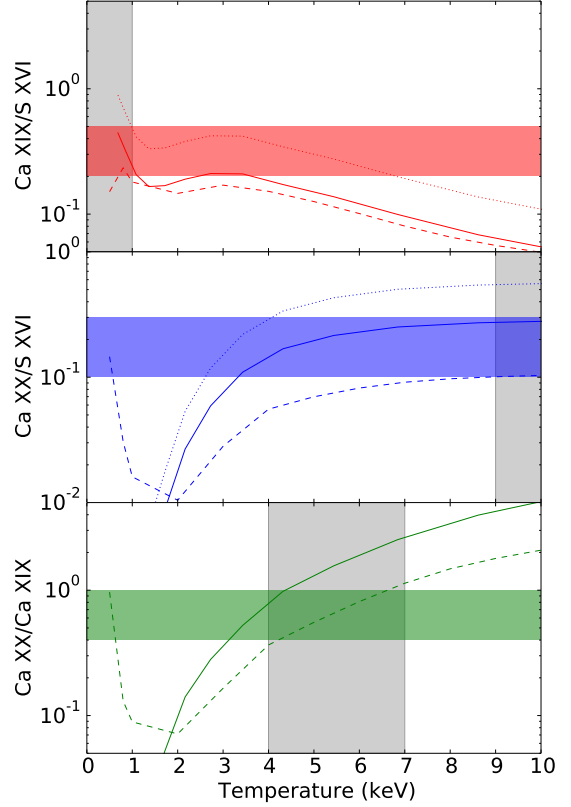


FIG. 2.— The line ratios for S XVI, Ca XIX, Ca XX from (solid line) AtomDB 2.0.2, (dotted line) AtomDB 2.0.2, assuming a sulfur abundance of 0.5 solar, and (dashed line) from the strong line approximation, as used by JP. The horizontal shaded bars show the range of observed values for the various cluster subsamples in B14. The gray shaded intervals show the valid temperature ranges as given by JP.

the bottom panel of Fig. 2). The color bands overplot the observed ratios for the Perseus MOS spectrum from the whole cluster (i.e., including the cool core), which should have a contribution from cool components. Yet, the two ratios show a remarkable agreement at $T \approx 3.5$ keV (which happens to be one of the continuum model components, see Table 2 of B14). This indicates that (a) the components emitting the bulk of the S and Ca lines have the same temperature and (b) any significant contribution from the components with $T < 2.5$ keV is excluded. Note that, while both Ca lines have very low emissivities at $T \sim 1$ keV (lower panel in Fig. 3) and one might argue that the Ca XX/Ca XIX ratio is insensitive to the presence of components at such low temperatures in a multi-temperature plasma, the S XV line is very strong at $T \sim 1$ keV, and so the S line ratio would be biased toward that component if it is present in the mix. In all the subsamples analyzed in B14, the S XVI/S XV ratio is above 1.8, which similarly excludes any large contributions from cool gas. Of course, we do know that cool-core clusters have a wide range of temperatures — but the relative contribution of the cool components into the emission of the relevant lines is small.

An independent consideration is the observed absolute line fluxes. Because the Ca XX, Ca XIX and S XVI emissivities drop steeply at low temperatures (lower panel in Fig. 3), any cool component would have to have a very

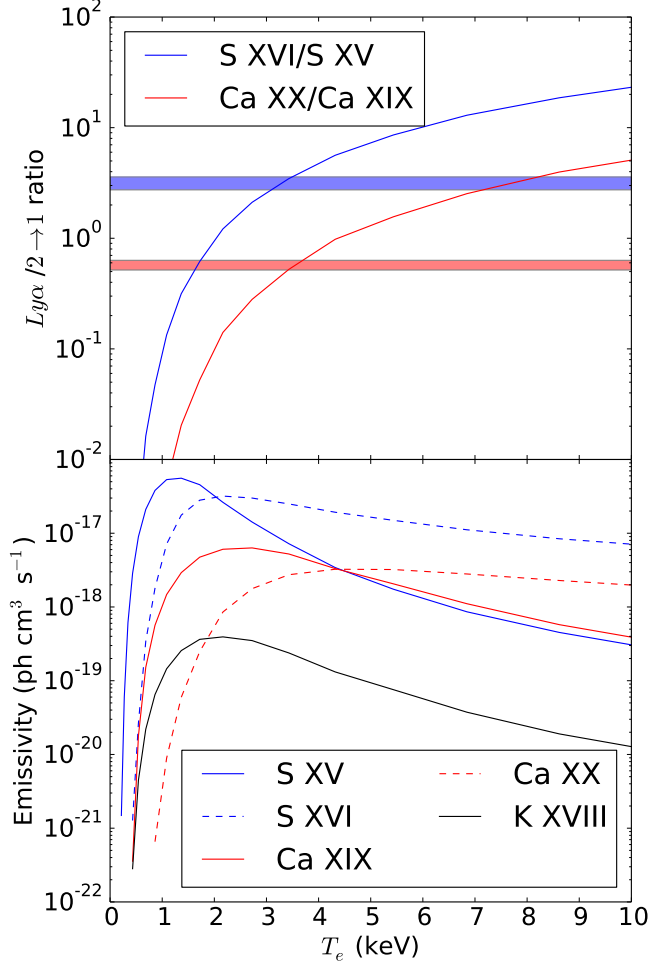


FIG. 3.— *Top*: Emissivity ratios for S XVI/S XV and Ca XX/Ca XIX, with the observed values from the Perseus MOS full-cluster data shown by horizontal bands (representing 90% intervals). Both observed line ratios indicate the same $T \approx 3.5$ keV. *Bottom*: The emissivities of the above four features and the K XVIII line vs. temperature, from AtomDB 2.0.2.

high abundance of those elements to contribute significantly to the observed line fluxes. For example, to produce all of the observed Ca XX line in the Perseus MOS spectrum with a $T = 1$ keV plasma, the Ca abundance would have to be over 100 times solar (which is unlikely given the observed values of 0.3 – 2 solar in clusters, including their cool cores).

As a side note, the lower panel of Fig. 3 also shows the emissivity of the K XVIII line alongside the S and Ca ions. The S and Ca lines peak at similar temperatures and straddle the peak of the K line, which is why these ions are a particularly good predictor for K XVIII and were used for this purpose in B14.

1.3. Potassium

The possible contribution of K XVIII to the spectrum was a major concern in B14, hence the extensive discussion of the potential contribution from this line, and its inclusion in all fits. Therefore, the relevant question is not the strength of the K XVIII line relative to the unidentified line, but whether or not the fits require an unidentified line *in addition to* the K XVIII.

We consider the specific case highlighted by JP, that of the K XVIII line in the Perseus MOS observations. For all K XVIII flux estimates here, we will use the sum of the 3.47 keV and 3.51 keV components, as in JP. Looking again at Fig. 3, the observed S XVI/S XV and Ca XX/Ca XIX ratios indicate a remarkably consistent $T \approx 3.5$ keV. If the underlying temperature is indeed 3.5 keV, the implied K XVIII triplet flux, assuming solar elemental abundance ratios, is $1.05 \pm 0.06 \times 10^{-5}$ ph cm $^{-2}$ s $^{-1}$ if derived from Ca, and $0.74 \pm 0.02 \times 10^{-5}$ ph cm $^{-2}$ s $^{-1}$ if derived from S.

In Table 3 of B14, the Perseus MOS has a total predicted flux for the K XVIII line of $0.64 \pm 0.34 \times 10^{-5}$ ph cm $^{-2}$ s $^{-1}$ (the difference from the above values, within the uncertainty, is due to the two-component modeling and the averaging over three lines in B14). Given the uncertainties involved in this prediction (e.g., the relative element abundances), we applied very broad bounds on our line fits, allowing them to range from 0.1 – $3 \times$ our predicted values — including their errors. (Note from Fig. 3 that the maximum emissivity of the K XVIII for any temperature is less than a factor 2 above the value at the temperature given by the above line ratios.) Thus, our fit allowed the K XVIII to rise to 3×10^{-5} ph cm $^{-2}$ s $^{-1}$ in this spectrum.

With this cap on the K XVIII line, the spectrum did require the additional line at $E \approx 3.57$ keV. In §3.4 of B14 we performed several tests removing the caps on the K XVIII line and the Ar XVII DR line at a higher energy, and concluded (see also §6 in B14) that the new line is not significantly detected only if both these lines are allowed to be above their upper limits by large factors.

Note that, although JP did not comment on this, their highest predicted K XVIII flux based on the Ca XIX line (from the Perseus flux in Table 2 of B14 and the ratios from Tables 3 and 2 in JP — that is, using the incorrect atomic data) is 3.1×10^{-5} ph cm $^{-2}$ s $^{-1}$, assuming a temperature of 1 keV. This flux is in the range that we allowed for K XVIII in the fit in B14 (see above). Estimates based on the Ca XX line at low temperatures are irrelevant (because of the exorbitant Ca abundance required, see §1.2 above); at higher temperatures, their estimates based on Ca XX (as well as the estimates from S XVI for all temperatures) were again within our allowed bounds for K XVIII.

1.4. Chlorine

The Cl XVII line in question is the Ly β doublet. In a thermal plasma, it is always much weaker than the Ly α doublet at $E = 2.96$ keV. A theoretical ratio of these lines as a function of temperature is shown in Figure 4 for collisional ionization equilibrium (CIE), taken from AtomDB 2.0.2 (Foster et al. 2012). For completeness, we also show a limit corresponding to charge exchange (CX), another possibly relevant nonthermal mechanism (although, as discussed in B14, there has been no evidence for any significant CX emission in clusters). The CX models of Smith et al. (2014) do not contain Cl, so we took it to be equal to the limit for S and Ar, which should be similar. For all temperatures, both CIE and CX Ly α /Ly β ratios are above 6.

We did not include the Cl XVIII lines in B14, because their expected fluxes (based on the APEC CIE model) were below our threshold, but we can easily check if the

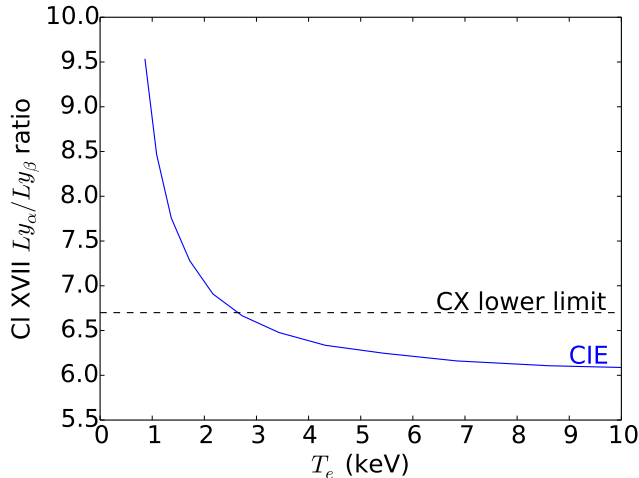


FIG. 4.— The Cl XVII $\text{Ly}\alpha/\text{Ly}\beta$ ratio from AtomDB 2.0.2

requisite $\text{Ly}\alpha$ emission is present. Taking the MOS data for the full Perseus cluster used in B14, we extended the spectral fit region from $E = 3\text{--}6$ keV to $2.55\text{--}6$ keV, and included 2 additional Gaussian components, at $E = 2.62$ keV for S XV and at $E = 2.96$ keV for the Cl XVII $\text{Ly}\alpha$ line. We do not detect the Cl XVII $\text{Ly}\alpha$ line (which has so far not been observed in any cluster) and can place a 90% upper limit on its flux of 5.7×10^{-6} phot $\text{cm}^{-2} \text{s}^{-1}$. This implies a maximum flux for the $\text{Ly}\beta$ line of 9.5×10^{-7} phot $\text{cm}^{-2} \text{s}^{-1}$, conservatively assuming the line ratio of 6. This is less than 3% of the maximum allowed flux for the model K XVIII line at the same energy in B14 modeling of the same Perseus spectrum. We note that while fitting the Galactic Center, JP apparently did not need to include the Cl XVII $\text{Ly}\alpha$ line either, in which case the Cl $\text{Ly}\beta$ should also be negligible. To have a $\text{Ly}\beta$ line in the absence of the $\text{Ly}\alpha$ line for any ion would be even more exotic than sterile neutrino.

2. CONCLUSIONS

We conclude that the JP analysis is severely affected by their use of the approximate atomic data. When the correct atomic data are used, the line ratios of S and Ca do not indicate a wide and inconsistent range of temperatures in clusters, contrary to JP's conclusion. In fact, for the fiducial and interesting case of Perseus, the S and Ca line ratios — in particular, those disentangled from the relative elemental abundances — are consistent and indicate a reasonable plasma temperature. They also exclude significant contributions from cool plasma components to the Ca and S lines and thus to the possible K XVIII line (a potential contaminant for the B14 result) in Perseus and other cluster samples considered in B14. However, even the K XVIII fluxes predicted by JP using their atomic data (excluding the highly implausible estimates based on Ca XX) have already been allowed by the very conservative B14 fits; the additional unidentified line was still required. As for the contaminating Cl XVII line proposed by JP that was not included in

B14 modeling, this would be a $\text{Ly}\beta$ line with the absent $\text{Ly}\alpha$ line from the same ion, which is highly unexpected. We conclude that the 3.5 keV line detection in B14 is not affected — with the detailed caveats given in B14.

We have concentrated on the galaxy cluster analysis in JP, although the bulk of their paper deals with Galactic Center. The incorrect use of atomic data will affect all of the results; in particular, it may lead to an incorrect conclusion that a large range of temperatures is not only possible, but required, to model both the Galactic Center and other systems. As it happens, the conservative fitting procedure used by B14 makes this irrelevant for the analysis in B14, but for the benefit of the researchers studying other objects, we include the correct data in the Appendix.

3. APPENDIX: LINE SELECTION

We have no reason to doubt the fluxes shown in Table 2 of JP. However, their choice of lines to include when converting the observed line fluxes into predicted K XVIII fluxes for Table 3 is questionable. As an example, for the He-like Ar XVII line they include lines at 3.124, 3.126 and 3.140 keV, the resonance and two intercombination lines of the system. The forbidden line at 3.104 keV, well inside typical CCD energy resolution, was omitted, although it carries $\approx 25\%$ of the flux of this triplet.

Conversely, for the highest energy line in the sample, the Ca XX line at 4.1 keV, they have included the Ca XX $2p - 1s$ doublet, along with the $1s7p - 1s^2$, $1s8p - 1s^2$, $1s9p - 1s^2$ and $1s10p - 1s^2$ transitions of Ar XVII, and the K XVIII $1s3p - 1s^2$ transition. These extra lines are largely included for the low temperature limit, where JP claims the Ar lines “dominate”, yet the intervening $1s3p - 1s^2$, $1s4p - 1s^2$, $1s5p - 1s^2$ and $1s6p - 1s^2$ lines at 3.68, 3.87, 3.97 and 4.01 keV respectively are not noted as being stronger than the 4.1 keV line, which they must be if they originate from Ar.

In Table 1 we show the values of the emissivity of the K XVIII $1s2p - 1s^2$ triplet predicted by these line fluxes listed in Table 2 of JP for the MOS detector. The top half shows the emissivities as calculated using their line list, the bottom using ours, using AtomDB 2.0.2. The exact lines that we have included, compared with those included by JP, are listed in Table 2.

TABLE 1
REVISED FLUXES (PH $\text{CM}^{-2} \text{S}^{-1}$) FOR JP TABLE 3 OF THE K XVIII
 $n = 2 \rightarrow 1$ TRIPLET BASED ON THE GALACTIC CENTER FLUXES
PRESENTED IN JP TABLE 2, USING ATOMDB 2.0.2

Te(keV)	S XVI	Ar XVII (3.13keV)	Ar XVII (3.69keV)	Ca XIX	Ca XX
Using original JP lines					
0.8	6.1e-06	8.0e-06	1.9e-05	2.4e-05	1.6e-04
1.0	3.6e-06	9.5e-06	1.9e-05	2.0e-05	1.2e-04
2.0	2.1e-06	1.7e-05	2.3e-05	1.5e-05	2.4e-05
5.0	1.3e-06	3.7e-05	4.1e-05	1.2e-05	1.8e-06
Using our recommended lines					
0.8	6.1e-06	5.8e-06	1.8e-05	2.4e-05	2.6e-03
1.0	3.5e-06	6.8e-06	1.7e-05	2.0e-05	1.2e-03
2.0	1.8e-06	1.1e-05	1.9e-05	1.3e-05	2.6e-05
5.0	7.9e-07	1.8e-05	2.4e-05	7.2e-06	1.1e-06

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TABLE 2
THE LINES INCLUDED IN THE 6 LINE COMPLEXES IDENTIFIED BY
JP, IN THEIR WORK AND IN B14.

Feature	Lines (JP)	Lines (This work)
S XVI	$2p\ ^2P_{1/2} \rightarrow 1s\ ^2S_{1/2}$ $2p\ ^2P_{3/2} \rightarrow 1s\ ^2S_{1/2}$	$2p\ ^2P_{1/2} \rightarrow 1s\ ^2S_{1/2}$ $2p\ ^2P_{1/2} \rightarrow 1s\ ^2S_{1/2}$
Ar XVII ^a 3.13 keV	$1s2p\ ^1P_1 \rightarrow 1s^2\ ^1S_0$ $1s2p\ ^3P_2 \rightarrow 1s^2\ ^1S_0$ $1s2p\ ^3P_1 \rightarrow 1s^2\ ^1S_0$	$1s2p\ ^1P_1 \rightarrow 1s^2\ ^1S_0$ $1s2p\ ^3P_2 \rightarrow 1s^2\ ^1S_0$ $1s2p\ ^3P_1 \rightarrow 1s^2\ ^1S_0$ $1s2s\ ^3S_1 \rightarrow 1s^2\ ^1S_0$
Ar XVII 3.69 keV	$1s3p\ ^1P_1 \rightarrow 1s^2\ ^1S_0$	$1s3p\ ^1P_1 \rightarrow 1s^2\ ^1S_0$ $1s3p\ ^3P_1 \rightarrow 1s^2\ ^1S_0$
Ca XIX	$1s2p\ ^1P_1 \rightarrow 1s^2\ ^1S_0$ $1s2p\ ^3P_2 \rightarrow 1s^2\ ^1S_0$ $1s2p\ ^3P_1 \rightarrow 1s^2\ ^1S_0$ $1s2s\ ^3S_1 \rightarrow 1s^2\ ^1S_0$	$1s2p\ ^1P_1 \rightarrow 1s^2\ ^1S_0$ $1s2p\ ^3P_2 \rightarrow 1s^2\ ^1S_0$ $1s2p\ ^3P_1 \rightarrow 1s^2\ ^1S_0$ $1s2s\ ^3S_1 \rightarrow 1s^2\ ^1S_0$
Ca XX	Ca XX	
	$2p\ ^2P_{1/2} \rightarrow 1s\ ^2S_{1/2}$ $2p\ ^2P_{3/2} \rightarrow 1s\ ^2S_{1/2}$	$2p\ ^2P_{1/2} \rightarrow 1s\ ^2S_{1/2}$ $2p\ ^2P_{3/2} \rightarrow 1s\ ^2S_{1/2}$
	Ar XVII	
	$1s7p\ ^1P_1 \rightarrow 1s^2\ ^1S_0$ $1s8p\ ^1P_1 \rightarrow 1s^2\ ^1S_0$ $1s9p\ ^1P_1 \rightarrow 1s^2\ ^1S_0$ $1s10p\ ^1P_1 \rightarrow 1s^2\ ^1S_0$	
	K XVIII	
	$1s3p\ ^1P_1 \rightarrow 1s^2\ ^1S_0$	
K XVIII	K XVIII	
	$1s2p\ ^1P_1 \rightarrow 1s^2\ ^1S_0$ $1s2s\ ^3S_1 \rightarrow 1s^2\ ^1S_0$	$1s2p\ ^1P_1 \rightarrow 1s^2\ ^1S_0$ $1s2s\ ^3S_1 \rightarrow 1s^2\ ^1S_0$ $1s2p\ ^3P_2 \rightarrow 1s^2\ ^1S_0$ $1s2p\ ^3P_1 \rightarrow 1s^2\ ^1S_0$ ^b
	Cl XVII	
	$3p\ ^2P_{3/2} \rightarrow 1s\ ^2S_{1/2}$ $3p\ ^2P_{1/2} \rightarrow 1s\ ^2S_{1/2}$	

^aAr XVII 3.13 was included in the models of B14 but was not used to constrain the K XVIII emissivity

^bThese lines were not included in B14 as the forbidden and resonance lines were modeled as separate component, and their flux is $\approx 10\%$ of those. However, as JP use a single Gaussian for the feature, their flux should be included, and they have been in this comment

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